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THE USE OF VISUAL CUES FOR VEHICLE CONTROL AND NAVIGATION

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INTRODUCTION

At least three levels of control are required to operate most vehicles: (1) Inner-loop control to counteract the momentary effects of disturbances on vehicle position, (2) Intermittent maneuvers to avoid obstacles, and (3) Outer-loop control to maintain a planned route. Operators monitor dynamic optical relationships in their immediate surround to estimate momentary changes in forward, lateral, and vertical position, rates of change in speed and direction of motion, and distance from obstacles. They seek, identify, and locate specific landmarks to maintain more global geographical orientation. Mental rotation and transformation may be required to align information in maps, instruments, or memory into alignment with the visible scene for comparison. The process of searching the external scene to fmd landmarks (for navigation) is intermittent and deliberate, while monitoring and responding to subtle changes in the visual scene (for vehicle control) is relatively continuous and "automatic." However, since operators may perform both tasks simultaneously, the dynamic optical cues available for vehicle control task may be determined by the operator's direction of gaze for wayfmding.

Constraints imposed by the mission, the vehicle, and the environment determine the temporal and spatial precision with which operators can and should execute their activities, the information that is available, and the processes by which navigation and immediate control are accomplished. Routes may be explicit and visible in the extemal scene (i.e., roads), represented on displays in digital or analog formats (i.e., air routes), or evolve in response to information obtained and events that occur during the mission (i.e., maneuvering around unexpected obstacles) . Operators rely on a variety of information sources and reference systems to accomplish each level of control. However, the utility of information for different control functions varies within and between missions, depending on the operator's goals and experience and the unique characteristics of the vehicle and the environment.

The following is an attempt to relate the visual processes involved in vehicle control and wayfinding. The frames of reference and information used by different operators (e.g., automobile drivers, airlme pilots, and helicopter pilots) will be reviewed with particular emphasis on the special problems encountered by helicopter pilots flying nap of the earth (NOE). The goal of this overview is to describe the context within which different vehicle control tasks are performed and to suggest ways in which the use of visual cues for geographical orientation might influence visually guided control activities.

AUTOMOBILE DRIVERS

When driving a car, the current route and choice points are immediately visible. Furthermore, target performance criteria are well defined: (l) Speed limits are posted or drivers may match their speed to the flow of traffic, and (2) Lateral position is constrained by the width of the road or the driver's lane.

Navigation

To maintain geographical orientation, an automobile driver's knowledge of an area does not have to extend very far beyond the road system. If he is on the correct road, traveling in the correct direction, and can recognize relevant choice points, he does not need to know exactly where he is most of the time nor anything about the streets, structures, or terrain features on either side of his route. Drivers need to refer to other coordinate systems (e.g., compass direction) only when making decisions about which way to turn at an unfamiliar intersection where options are distinguished by North/South or East/West. In most cases, drivers can navigate well even at night, in poor visibility, and in unfamiliar areas because their options are limited by the structure of the road system.

Thus, the mental models drivers develop of their environment are composed of major arteries (e.g., their names, orientation, or end points), the relationships among them (e.g., significant intersections, or relative orientations and distances), and detailed information about secondary roads in specific areas. They may organize information about isolated groups of familiar secondary roads by their proximity to major arteries, specific places, or geographical features. In addition, people can infer the location of an unfamiliar place if streets are laid out in a regular pattern and named in a logical sequence. Automobile drivers develop mental models of familiar environments through experience. They elaborate these models over time, incorporating new information about previously unfamiliar areas or additional information about familiar areas.

When driving from one place to another, people plan and follow a route by refernng to: (l) remembered or written route lists (e.g., street names, turn directions, and time or distances between turns; (2) remembered spatial relationships among streets (whose names may not be known), (3) visible landmarks, and/or (4) maps. When driving to an unfamiliar place in a generally familiar area, they can develop an approximate route based on their general knowledge of the area, while they must rely on explicit instructions or a map in an unfamiliar area.

Figure 1 depicts a typical road map used by automobile drivers. Figure 2 depicts a more spatially compatible perspective view that integrates major highways with significant terrain features and landmarks. The latter type of map provides a driver, that is unfamiliar with an area, with explicit cues about how landmarks will look and the relationships among traffic routes, terrain, and significant cultural features.

Automobile drivers are generally free to choose any route they wish and deviate from a planned route at any time; there are no externally imposed constraints on departure times, route selections, or route changes. Enroute, they may verify that they are on course by identifying features along the way or reading road signs. If they are not sure where they are, they may have sufficient general knowledge of the area to locate a familiar feature to re-orient themselves. The selection (or change) of routes and departure, enroute, or arrival times are usually based on personal time constraints (e.g., a desire to arrive at work on time). To maintain a schedule, drivers estimate where they are, the distance from their destination, and probable driving time based on past experience or mental arithmetic. If they encounter traffic congestion or road construction they may switch to another route or adjust their speed. The number of options available to drivers are determined by the availability of alternate routes and their knowledge of the area.

In an unfamiliar area, drivers may use cues and representations that are similar to those used in familiar areas, but their knowledge of the environment is limited to a few highways, significant intersections, and landmarks. Their mental models are sparse and may be based solely on the quick review of a map. Their time/distance judgments are likely to be less accurate and they have limited flexibility if they encounter problems using the planned route. If they miss a turn, or turn in the wrong direction, they may have to retrace their steps or consult a map to figure out where they are.

When giving directions or acting as a navigator from the passenger's seat, people generally refer to roads or places by name and give instructions oriented to the driver's frame of reference ("Turn right at the stop sign."). They may refer to compass directions to improve the general geographical orientation of the recipient ("The park is 2 miles South of the intersection.") or identify a specific location ("The store is located on the Northeast side of the intersection."). They may provide additional information about boundaries ("If you pass the mall, you have gone too far."), choice points ("Turn right on 1st Street just past the park."), or distances ("The intersection is in 2 miles."). Finally, they may provide predictive information to allow the driver to plan ahead ("Stay to the right after the bridge."). In most cases, people use explicit names and distinctive, visible features to aid recognition. This process is facilitated if both individuals share a common knowledge of the area. If they do not, then verbal labels may have to be supplemented with a description of significant landmarks.

Vehicle Control

In an automobile, drivers rely on visual cues for both vehicle control and navigation, rather than on instruments. They continuously scan the environment to avoid obstacles and regulate speed and lateral position. Although they can refer to the speedometer to determine their actual speed, most control inputs reflect estimates of absolute speed, relative speed (in comparison to other automobiles), or changes in speed that have already occurred or will occur (e.g., when approaching hills or slower traffic). These estimates may be based on optical cues (e.g., optical flow, edge rate, rate of closure with moving or stationary objects), auditory cues, or vibration. The accuracy of such estimates may be reduced when operating an unfamiliar automobile; if the driver's eye height is significantly higher or lower than usual (because the vehicle is a different size), there may be a consistent bias in speed estimates.

Lateral control is primarily based on optical cues; drivers generally try to remain centered in their lane and safely separated from other traffic. When driving in a cross wind, drivers compensate by adopting a constant bias in their control input. The frequency with which lateral control inputs are required depends on the road surface and traffic density. Required control precision depends upon lane width, car width, and traffic density.

AIRLINE PILOTS

The pilots of commercial jets are faced with a different situation. They fly high above the earth where there are no visible routes to follow and environmental cues are few and far between. Although they could use the sun and stars for navigation, celestial navigation is difficult, imprecise, and impossible when the sky is obscured by clouds. Alternatively, they might refer to significant landforms to improve their geographical orientation. However, these cues might be too distant to use as a primary cue or invisible in poor weather or at high altitudes. Thus, pilots generally rely on instruments for navigation and flightpath control.

Navigation

Given the increasing density of air traffic, greater navigational precision and coordination have become necessary. Thus, formal route structures have been created that are defined by arbitrary coordinate systems referenced to agreed upon standards (e.g., magnetic north) and a network of navigation aids. Information from these sources provide "pathways" for pilots to follow which are not directly visible but instantiated on instruments, displays, and charts.

Pilots must integrate dynamic information presented in different formats (digital/analog), spatial dimensions (one-dimensional/two-dimensional), and units (knots, degrees, feet) that are referenced to many different coordinate systems (earth referenced—intertial, magnetic or polar coordinates; vehicle referenced—longitudinal, vertical, and lateral axes) to develop a dynamic, three-dimensional mental model of the environment. Furthermore, traditional cockpit instruments are not referenced to the ground below. Thus, pilots must infer their position and ground speed. For example, a magnetic compass displays heading rather than ground track; winds may cause the craft to drift off course, while the aircraft's heading remains constant. Airspeed indicators display rate of movement through the air rather than across the ground. Barometric altimeters display height above sea level rather than height above landforms immediately below the aircraft.

In general, airline pilots' knowledge about their location is referenced to these (invisible) route structures, which are superimposed upon, but not necessarily related to terrain features. These systems allow very precise navigation, even when visibility is zero, but require the human operators to maintain very complex mental models of their environment. Because the air route structure is the basic reference system, rather than visible terrain features, pilots may not be "lost" even if they have no idea what state they are flying over; as long as they are on time and on course, they know all they need to know. As with automobile drivers, pilots' mental models of the environment, and the degree of precision with which they must maintain geographical orientation is substantially constrained by the route structure within which they operate. However, they may also incorporate information about terrain features, weather systems, and other vehicles (from visual observation or radio communications) into their mental models.

In aviation, flight plans are based not only on altitudes and bearings, but also on time. In order for the air traffic control system to operate smoothly, pilots must depart and land on time, and arrive at "fixes" (imaginary points in the sky that represent the intersection of two radio navigation signals) on schedule. Although these nominal times are worked out in advance, based on the aircraft's speed and predicted wind conditions, the situation may change. Thus, pilots may have to adjust their speed to stay on schedule. However, in conventional aircraft, pilots must infer the distance they have traveled across the ground, as their instruments display airspeed, rather than groundspeed.

Enroute, pilots communicate about their current position and planned route within the context of these arbitrary reference systems (e.g., heading, distance from a navigation aid, arrival at a "fix"). The language they use is highly structured and constrained to facilitate accurate and rapid transmission of information. They maintain geographical orientation by correlating the information viewed on their instruments with paper charts. Figure 3 depicts a high-altitude chart used in flight above 18,000 ft.

The only time pilots must adopt a frame of reference based on directly visible cues is during landing. At this point, they must transition from one mental model (based on an arbitrary route structure) to another (visible structures and terrain features viewed in the external scene). In addition, they may compare visible cues to those depicted on an approach plate. Figure 4 depicts an approach plate used when landing at an airport. It includes some information about visible landmarks as well as the route the pilot is to follow. After transitioning to a visual frame of reference, pilots may report their position with respect to visible landmarks whose location is likely to be known by the message recipient.

Vehicle Control

During high-altitude flight phases, airline pilots base their manual control inputs on dynamic optical cues displayed on instruments; speed, altitude, and course are regulated by detecting and reducing errors between the target value and the current value. In some cases, the same instruments are used for vehicle control as for navigation. The effects of wind on ground speed and ground track must be inferred.

The spatial relationship between movement of an indicator on an instruments, control inputs, and movement through space are often incompatible. For example, the effects of right/left control inputs to changes in heading are reflected in rotation of the compass in the opposite direction (the display is "inside-out"). Fore/aft throttle inputs are reflected in rotations of the airspeed indicator (clockwise, faster; counterclockwise, slower). Fore/aft inputs in the control yoke and/or the throttle affect attitude and power, which determine altitude. The altimeter depicts height above the ground (radar altimeter) or above sea level (barometric altimeter) in two formats: digital readout (coarse-grained) and circular dial (fine-grained). Flight-directors are the only instrument that provides information about pitch, roll, yaw, and deviation from desired course in a spatially compatible format. However, these displays are "inside-out" (e.g., the "world" moves, while the "aircraft" remains stationary in the center of the display) and two dimensional, rather than perspective.

Although each instrument provides information about a specific dimension (e.g., altitude, airspeed, attitude), control inputs may influence more than one dimension (e.g., changes in altitude will also affect speed unless pilots compensate by adjusting the power setting). Rather than entering constant adjustments, most pilots wait until error has exceeded a criterion value; in most cases, smooth control is more important than precise control, to ensure passenger comfort. In all modern aircraft, autopilots allow pilots to set desired values by entering discrete commands; automatic subsystems achieve and then maintain the selected values at the specified times. Pilots simply monitor the system to ensure that it is functioning properly. When acting as either manual controllers or monitors of automatic systems, pilots must maintain an integrated, multidimensional model of vehicle state based on input from many sources expressed in different units of measurement and reference systems.

Only in the initial and final phases of flight, when departing from or approaching an airport, do pilots refer to dynamic optical cues visible in the external scene to monitor lateral position, altitude, and speed. Their task is more complex than that of automobile drivers: (1) They must worry about additional degrees of freedom (e.g., height above the ground, attitude, bank angle); (2) They are traveling three to four times faster and, thus, require greater visual range; and (3) They must relate their estimates of vehicle motion based on dynamic optical cues in the external scene to values displayed on instruments.

HELICOPTER PILOTS

The pilots of military or civilian helicopters flying at very low altitudes are faced with an even more difficult situation. They operate so close to the ground that local terrain features may obscure their view of significant landmarks and restrict their visual range. This makes it difficult to relate local terrain features to a more global context. Often, helicopters move freely through terrain, without an explicit (visible or electronic) route to follow. While there are many degrees of freedom in this environment (helicopter crews are not limited to roads or electronic routes), it is more difficult to maintain the desired course and natural and man-made obstacles pose a very real threat. In this environment, helicopter crews must correlate cues viewed in the external scene with information on paper maps to maintain geographical orientation, avoid obstacles, and maintain their course. Instruments that provide pilots with information about speed and altitude are relatively inaccurate at low altitudes and slow speeds and electronic aids must have a line of sight with the source to work properly.

Navigation

Before a mission, helicopter crews study maps of the environment in which they will operate to select a route that offers the most direct path to the destination (given terrain contours, obstacles, etc.), distinctive visual cues (to aid in geographical orientation), and cover (if there is an enemy threat). They select specific features that they will use during the mission to verify their location and identify choice points (e.g., intersections of rivers, hill tops, clearings, groves of trees). They might identify linear features that can provide a visible "route" to follow (e.g., ridge lines, river valleys). Military crews avoid selecting man-made structures for reference (things change) and following roads (the enemy threat is greater there).

Helicopter crews incorporate available information into a cognitive model or mental map of the environment through which they will travel. The mental representation might be spatial—a mental image of the map (a plan view) or a series of perspective mental images of how significant features in the environment are likely to look when viewed from the cockpit of a helicopter (a forward view). Alternatively, they may store this information as a route list—a series of verbal commands (e.g., "Travel down the valley for 2 miles then bear right") or descriptions (e.g., "Follow the creek that runs beside the cliff") that are remembered and executed during the mission.

During a mission, helicopter crews view features in the external scene and compare them to a paper map or their mental images. They must mentally transform the stylized images on two-dimensional maps into mental images, that represent a perspective view of the object. The image is then mentally rotated to bring it into alignment with the forward field of view for comparison with the external scene. If they continue to see expected features on time and in the correct order, they know where they are; visible terrain features correspond with their expectations and they can correlate their position with a location on the map. For example, when they pass a distinctive feature (e.g., a water tank depicted on their map) or intersecting linear features (e.g., two ridge lines), they know precisely where they are. However, if a single landmark is symmetrical, they may know generally where they are, but not their precise location or the direction from which they are approaching the feature. In this case, they may look for a second reference point, check the compass, look at the sun, or infer direction from previous cues. When using a ridge line that extends for some distance as a geographical reference, a crew only knows that they are traveling in the correct direction, but not their precise location.

Depending on the familiarity of the terrain, the availability of distinctive features, and the quality of pre-mission planning, maintaining a route may be relatively easy or very difficult. For example, when a crew must rely on subtle variations in terrain to judge location, it may be extremely difficult to relate features visible in the forward scene to contour lines on the map. This task is particularly difficult if surface contours are masked by vegetation. Furthermore, the appearance of terrain and vegetation varies seasonally and from one region to another, requiring adaptation and inference. There may be considerable ambiguity about whether a particular feature is, in fact, the one a crew expects to see, or the specific feature depicted on the map.

As the time between landmarks increases, uncertainty about current position may increase if additional cues are not available for the crew to verify that they are, in fact, where they think they are. At some point, the crew will begin to look for the next expected landmark. If it does not appear by the expected time, the crew may begin to consider the possibility that they are lost. If a feature that is similar to their expectations appears, the crew may identify it as the expected feature. If it is not, it make take some time before they accept the growing evidence that they are not where they are supposed to be. At this point, the crew must take action to re-establish their position. A helicopter pilot might gain altitude to find a distinctive landmark. If this is not possible, he may carefully survey the surrounding terrain and try to find a pattern of features on the map that corresponds to what he sees. However, it is much more difficult to find a pattern somewhere on a map that corresponds to the forward scene, than to verify that a visible feature is where it is supposed to be relative to the vehicle. Alternatively, tne pilot may try to re-trace his path until he finds a familiar landmark. However, the mental preparation performed before the mission will be of little help here, as terrain features and relationships will not correspond to the expected sequence or orientation.

Thus, maintaining geographical orientation requires helicopter crews to continuously correlate the visual scene with the map. Estimates of when to begin looking for a landmark, whether a choice point has been missed, or what features should be visible at any point in time are based on subjective estimates of the distance traveled and the time elapsed since the last known location. Explicit calculations are difficult because the route might not have been direct nor followed a straight line.

When operating at night, helicopter crews rely on night vision devices (that intensify light or display infrared imagery) to provide them with information about the external scene. Although they could not perform required missions without these devices, their use imposes considerable additional load on the pilots; field of view is limited, acuity is reduced, depth cues are distorted, subtle textures necessary to identify a particular feature may be missing, and objects or terrain features may look very different than expected. Furthermore, greater navigation precision is required at night; obstacles that can be seen and avoided during the day may be invisible at night. Thus, pilots rely on maps to spot potential obstacles. However, this information is useful only if they know exactly where they are. For these reasons, maintaining geographical orientation becomes significantly more difficult and overall prrformance capabilities may be reduced. For example, pilots are more likely to fly slower and higher at night.

In helicopters, crewmembers convey information about navigation and geographical orientation verbally, although they may use gestures, as well (e.g., point to features in the environment or on a map). In NOE flight, navigation may take as much as 90% of the navigator's time, and communications between the pilot and navigator about navigation, 25% of both crewmembers' time.

Army aviators use 1:50,000 scale maps (Figure 5) that depict terrain contours (e.g., hills, valleys), vegetation (e.g., fields, groves of trees) bodies of water (e.g., rivers, streams, ponds), and some cultural features (e.g., roads, buildings, bridges, water tanks, towers). During pre-mission planning, helicopter crews plot their route on the map, identify critical choice points, and select additional features that they will use to verify their position. In flight, the navigator follows the route of flight on the map, giving the pilot verbal cues about what he should see, when he should begin or end a turn, and potential obstacles. In addition, the navigator scans cockpit instruments, verbalizing relevant information to the pilot. The pilot generally keep his eyes on the forward scene, telling the navigator what he sees and verifying that he can (or can not) see a specific landmark.

Helicopter crews use (or mix) a number of frames of reference when exchanging information among themselves or transmitting to another vehicle: (l) ego-reference/spatial (e.g., a landmark is in front, to the right, or to the left of the pilot; the pilot should turn right or left); (2) ego-reference/clock position (e.g., a feature is at the observer's or recipient's 2 o'clock position); or (3) world-reference/compass heading (e.g., the pilot should look for a stream running North/South; the pilot should turn 20 degrees to a new heading of 280 degrees).

Ego-referenced directions are the easiest to process; they require minimal mental transformation or interpretation. Clock positions are less intuitively obvious than right/left directions, although they provide more precise information. However, clock position may be ambiguous if the sender's and receiver's points of reference (i.e., head position) are significantly different. Furthermore, extracting spatial information given in a verbal form may require additional mental transformations. When giving ego-referenced directions, the originator of the message must mentally project himself into the point of view of the intended recipient, an activity that imposes additional cognitive demands and is subject to error. Spatial information that is world-referenced (i.e., to a numeric or verbal compass position) is more precise than other forms, and does not require that the sender or recipient project themselves into another's ego-reference. However, steering commands referenced to compass position pre-suppose that the recipient knows the current heading. In helicopters, pilots may have no idea what their current heading is (they focus on the external scene, rather than the instruments).Thus,the navigator might couple an ego-referenced command (e.g., turn right) that requires minimal mental transformation with a world-referenced modifier (e.g., Turn right...Now you're heading due West) to improve the pilot's orientation.

In addition to the problems associated with the use of different reference systems, helicopter crews often operate in unfamiliar environments where crewmembers do not share a common knowledge base about the names and appearance of significant landmarks. Thus, information about these landmarks must be transferred on the basis of their physical appearance (e.g., a small round pond; a dry river bed; a saddle-back hill), rather than by name (i.e., Jones' farm; White Mountain; Route 50). Given the potential differences in personal experience, descriptive terms may also have very different meaning for different crewmembers. For example, what looks like a pond to one, may look like a lake to another. A 500 foot hill might look like a mountain to a mid-Westerner, while a pilot from Colorado might describe it as a small hill, and so on. Furthermore, lack of familiarity with local vegetation may make the description process particularly difficult; it is easier to identify a grove of trees by name than by their physical appearance.

Thus, the task of navigation for helicopter crews is quite different than it is for automobile drivers (whose current route is always visible and identified by road signs) or transport pilots (whose current route is displayed on an instrument and identified by an explicit value).

Vehicle Control

When flying at very low altitudes, helicopter pilots' vehicle control inputs are based primarily on visual cues extracted from the external scene. In this respect, their task is similar to that of automobile drivers (except that they must also regulate altitude). Since they do not have a visible route to follow, helicopter pilots regulate speed, heading, and altitude so as to maintain a safe speed (given their proximity to the ground and obstacles) and adequate clearance, while continuing to head in the general direction of their goal. Maintaining a specific altitude, speed, or heading is less important than remaining clear of obstacles. In addition, helicopter pilots must control not only the direction in which their vehicle is moving, but also its orientation (the tail rotor must not slew around and hit an obstruction to the side, rear or below the cockpit) and assure adequate clearance for the rotor blades (which extend beyond the width of the vehicle).

Because helicopter pilots must continuously move their heads and eyes to scan the environment to avoid obstacles and search for landmarks, the dynamic optical cues used for flight-path control are often viewed off-axis with respect to the direction of travel. This adds to the difficulty pilots encounter in using dynamic optical variables to regulate speed, heading, and course. Figure 6 presents the dynamic optical flow cues that might be available when a pilot is looking forward, 45 deg to the left or 90 degrees to the left. As you can see, the information provided is distinctly different.

Helicopter pilots estimate speed by interpreting dynamic visual cues in the environment or listening to the sound of the rotors. To estimate velocity from dynamic optical flow, however, they must also estimate their altitude; apparent speed depends on the pilot's height above the surface over which he is traveling. Alternatively, pilots may check their airspeed by looking at the instrument panel or by verbal information given to them by the navigator. Helicopter pilots estimate and maintain vertical and lateral trajectories and clearance from obstacles by monitoring the environment. They do not rely on instruments to control lateral or vertical position or rate when flying NOE. Again, information in the visual scene (e.g., dynamic optical flow, edge rate, and perspective transformations of features in the environment) is useful for detecting the effects of disturbances (e.g., winds) and pilot-induced deviations. As is the case with fixed-wing aircraft, control inputs affect more than one parameter. Thus, helicopter pilots must integrate their control activities to achieve a desired change. Because visible changes in optical variables may reflect changes in more than one axis, helicopter pilots must interpret the meaning of such changes, rather than responding to them directly (as they might when relying on instruments).

When flying with night vision devices, minification or magnification created by improper calibration or positioning of the lenses may impair the accuracy with which pilots can obtain dynamic motion cues. Furthermore, the reduced field of view that they provide (in current systems, the field of view is only 40 deg), limits the availability of peripheral motion cues. When using a helmet display of infrared imagery (such as provided in the AH-64 Apache helicopter), pilots face yet another problem. The sensor is located 3 ft below and 10 ft in front of the pilot's eye position. Thus, the pilot's visual reference is displaced. This produces systematic distortions: The vehicle appear to be moving faster and lower (because the sensor is closer to the ground than the pilot's usual visual reference) and obstacles seem closer than they are (because the sensor is forward of the pilot's usual visual reference). Since the display is presented on a monocle positioned in front of the pilot's right eye, binocular rivalry may be created by features visible in the external scene to the pilots' unaided left eye. Finally, symbology superimposed on the dynamic scene may interfere with the pilot's ability to detect subtle changes in the environment and create apparent-motion illusions.

SUMMARY

Automobile drivers, airline pilots, and helicopter pilots use their eyes to obtain information for both vehicle control and navigation. The process of searching the external scene to find landmarks (for navigation) is intermittent and deliberate, while monitoring and responding to subtle changes in the visual scene (for vehicle control) is relatively continuous and "automatic." However, since operators may perform both tasks simultaneously, the dynamic optical cues used for vehicle control may be determined by the operator's direction of gaze for wayfinding. In some cases, the visual information acquired for one type of control activity may simultaneously provide useful input for another; when a helicopter pilot looks at the forward scene to avoid obstacles, information about rate of movement is also available from the flow of terrain past the vehicle. Conversely, the visual requirements of one control task may interfere with the requirements of another; when an automobile driver turns his head to look at a sign, his vehicle may drift out of its lane. Thus, in order to understand the use of dynamic visual cues for regulating vehicle motion, the simultaneous tasks of navigation and obstacle avoidance must be considered; operators do not just use their eyes to look for dynamic optical cues. Rather, they often look for landmarks or at potential threats, and coincidentally extract motion cues useful for vehicle regulation. Since the operator is no longer looking in the direction that the vehicle is traveling, the optical relationships among cues in the visual scene may be somewhat misleading.

This chapter related the visual processes involved in vehicle control and wayfinding, contrasting the frames of reference and information used by automobile drivers, airline pilots, and helicopter pilots. The goal was to describe the contents within which different vehicle control tasks are performed and to suggest ways in which the use of visual cues for geographical orientation might influence visually guided control activities.

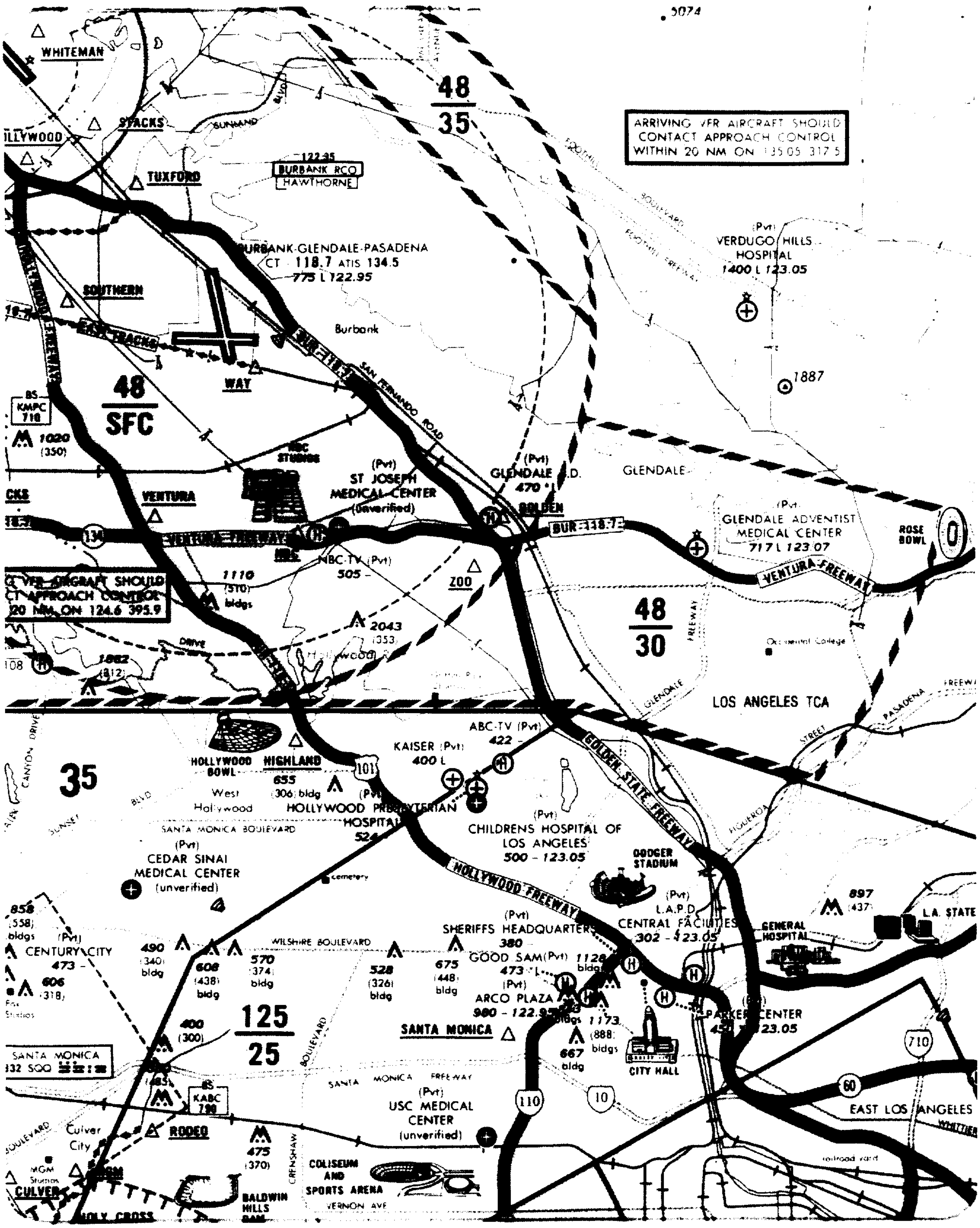

Figure 1. Helicopter low-altitude en route chart with iconic symbology.

Figure 2. 3-D conceptual chart of Los Angeles.

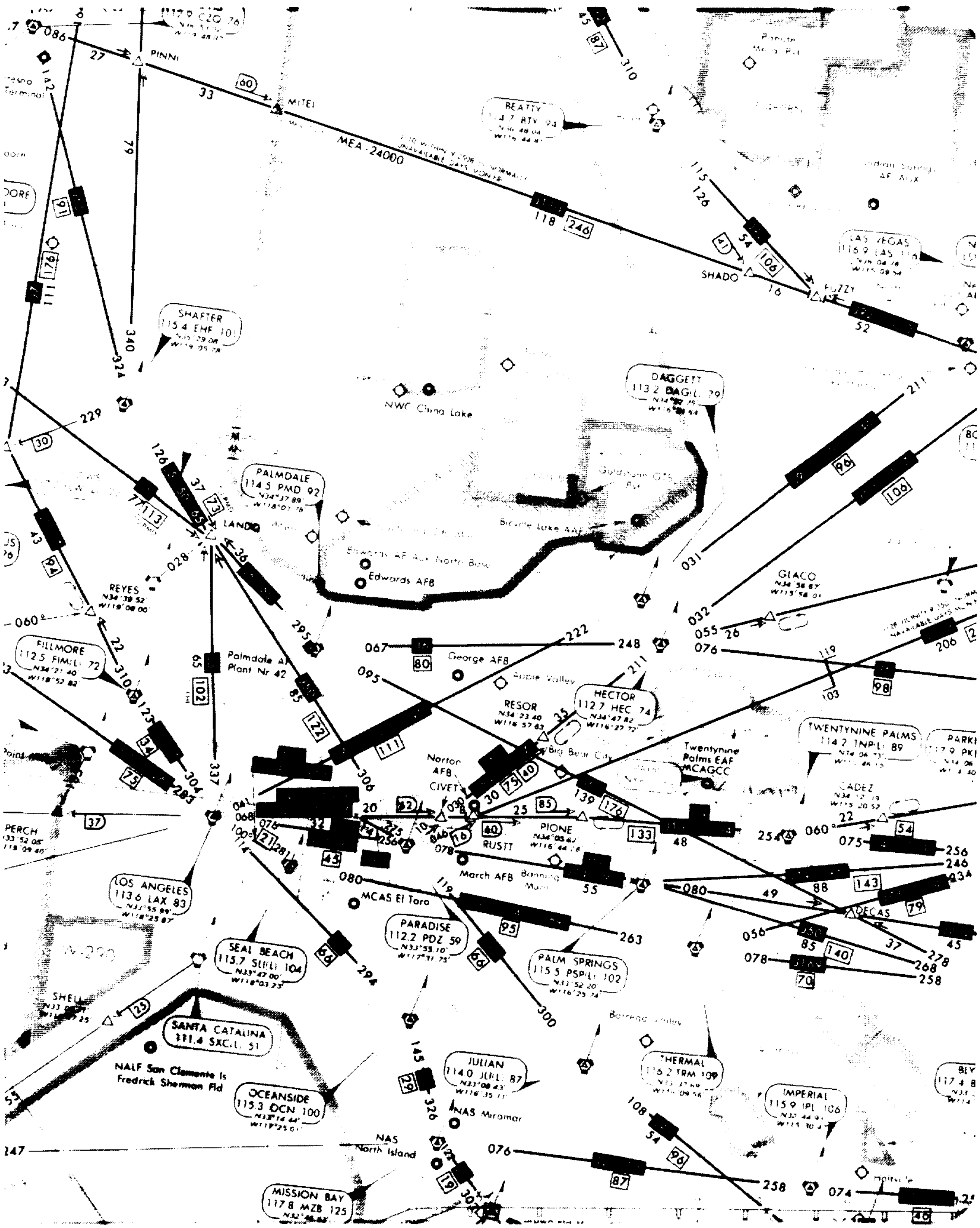

Figure 3. High-altitude en route chart.

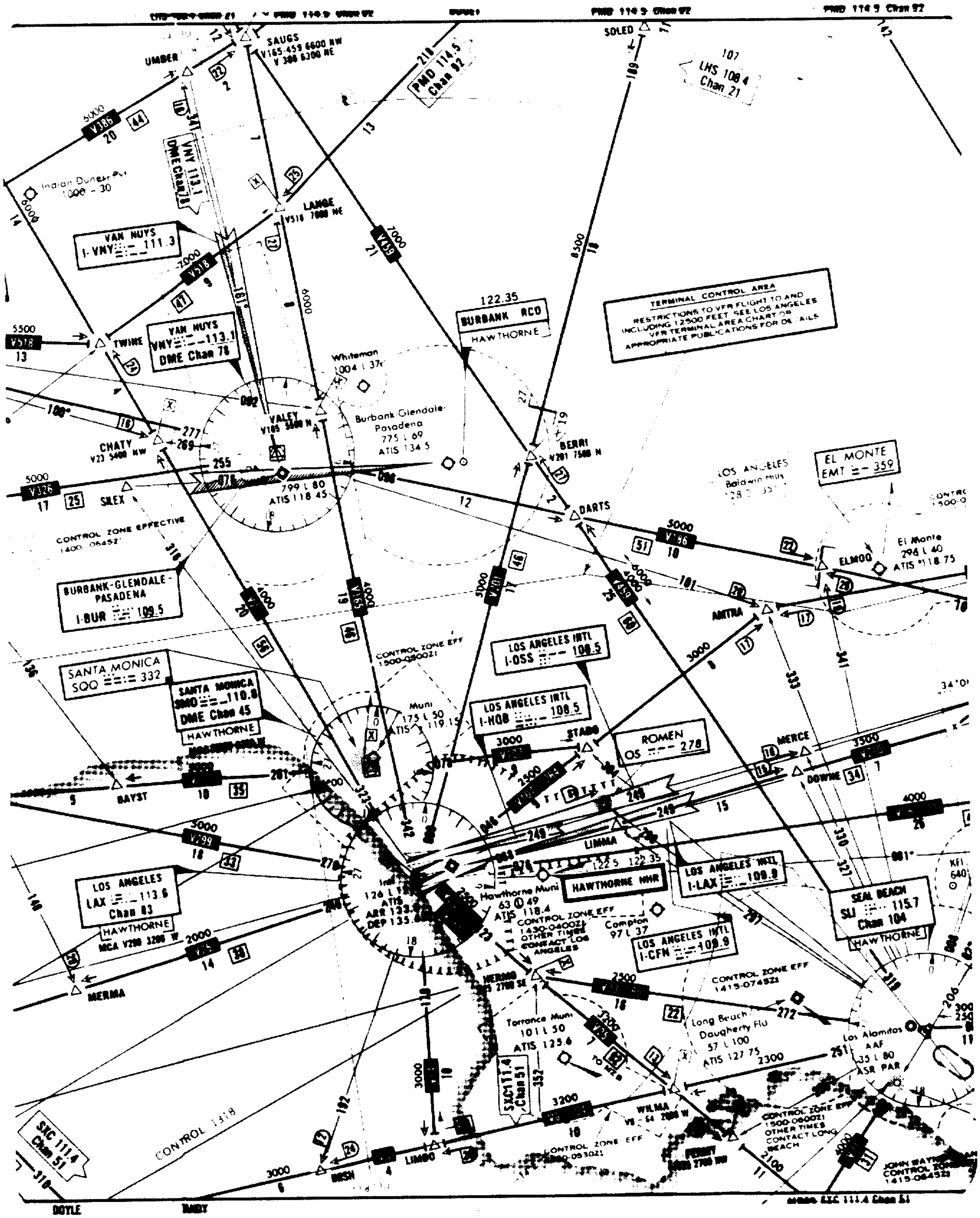

Figure 4. Low-altitude en route chart.

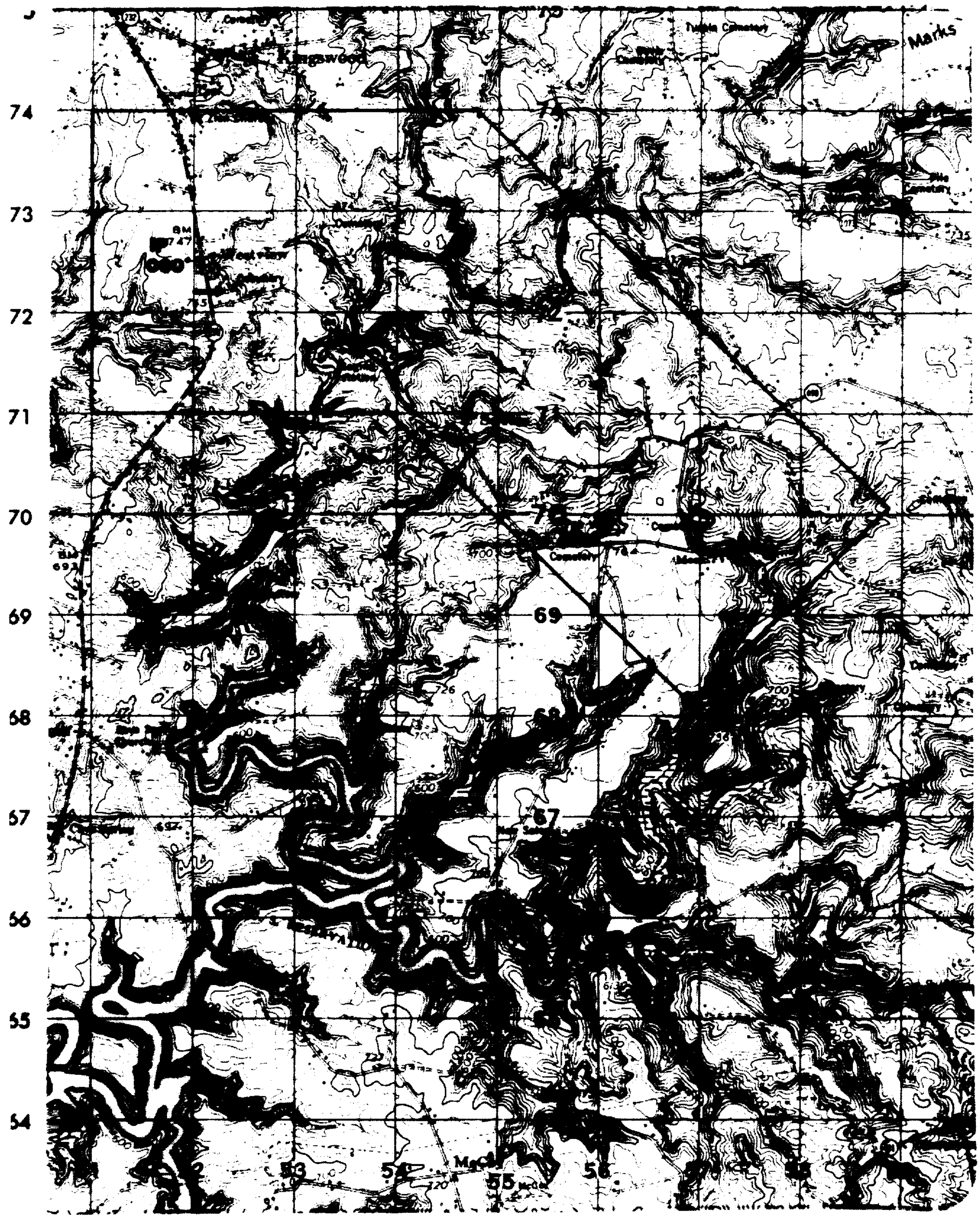

Figure 5. DMA 1:50,000 tactical navigation chart.

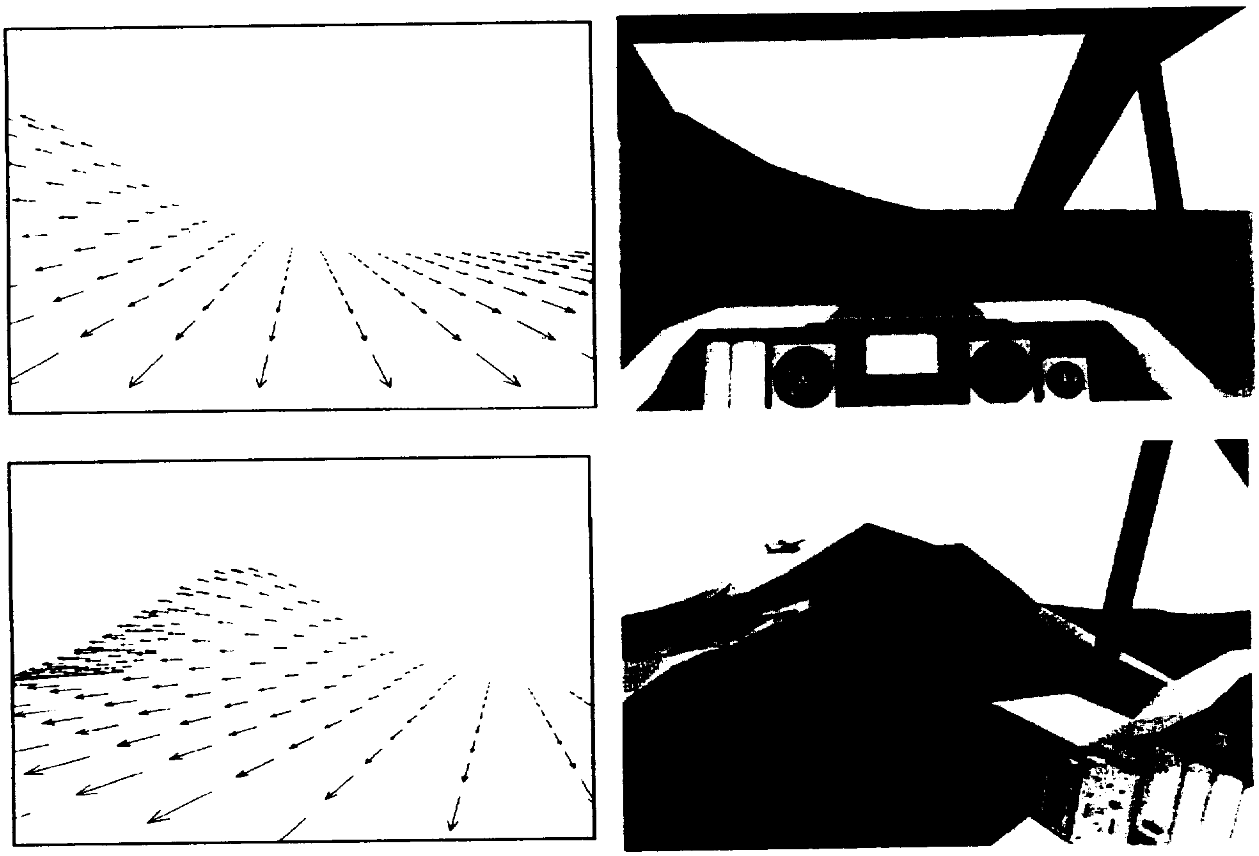

Figure 6. Helicopter forward and left window views and flow fields.